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aeromagnetic data, Mackenzie Valley,
Northwest Territories**

*Lawrence B. Aspler, Mark Pilkington, and
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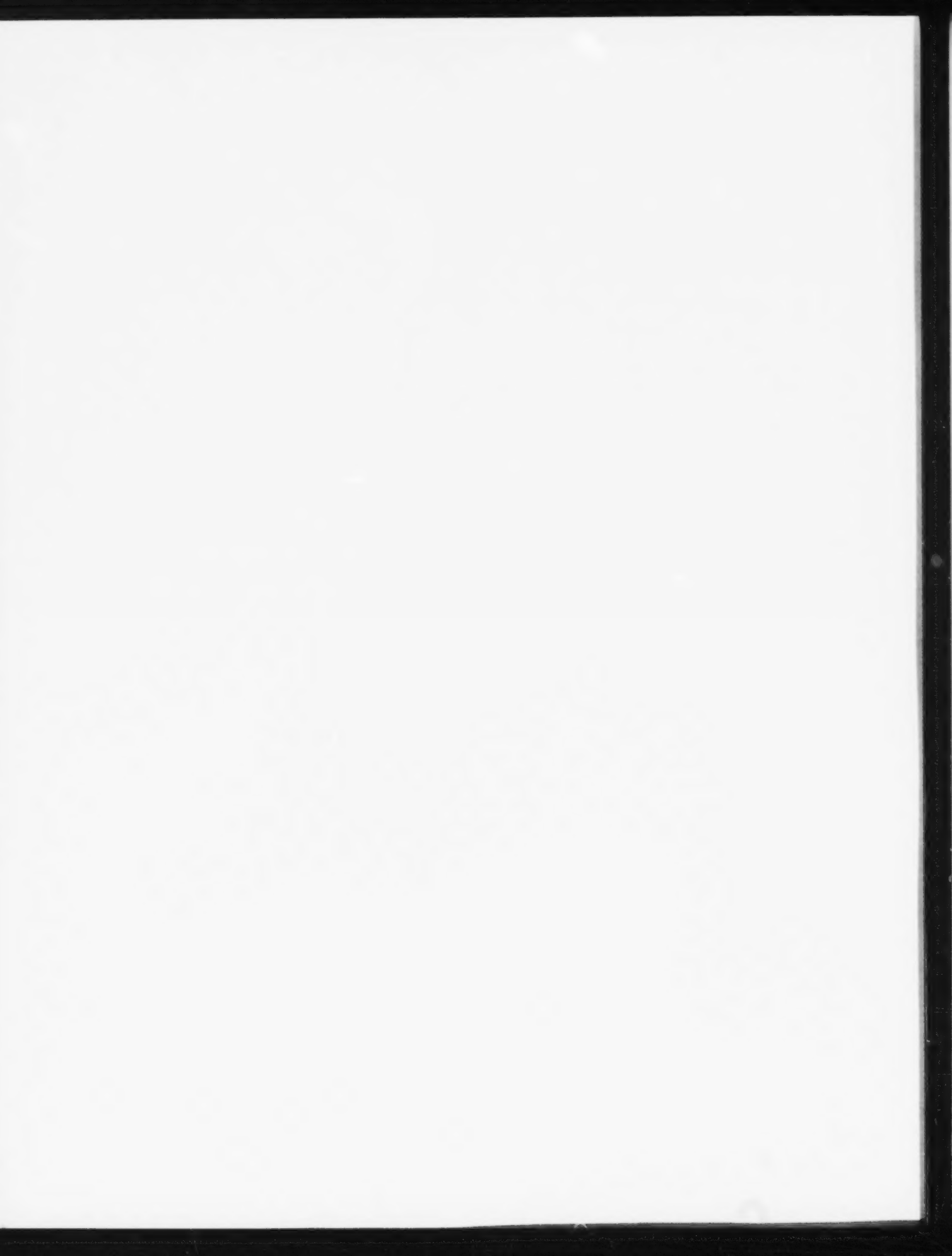
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Interpretations of Precambrian basement based on recent aeromagnetic data, Mackenzie Valley, Northwest Territories

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Abstract: Between 1998 and 2001, the Geological Survey of Canada acquired new aeromagnetic data over the northern Mackenzie Valley, a region of long-standing hydrocarbon and mineral potential. The new data point to a hitherto unidentified structure ('Cape Bathurst line') extending from western Great Bear Lake to Cape Bathurst. This structure may define the western limit of the Slave Province and truncate the Great Bear magmatic zone (eastern Wopmay Orogen). The data also suggest that the Fort Simpson magnetic high continues west to the Tintina Fault. Although the anomaly apparently has a source in crystalline basement, we cannot demonstrate that it represents a single tectonic entity (Fort Simpson terrane) along its entire length. The style of thrusting in the Colville Hills during the ca. 1.66 Ga Forward Orogeny has been controversial; magnetic modelling is consistent with crystalline basement-involved thrusting, but does not preclude thin-skinned interpretations.

Résumé : Entre 1998 et 2001, la Commission géologique du Canada a acquis de nouvelles données aéromagnétiques au-dessus de la partie nord de la vallée du Mackenzie, une région dont le potentiel minéral et celui en hydrocarbures sont reconnus depuis longtemps. Les nouvelles données laissent supposer l'existence d'une structure non identifiée jusqu'à présent (« ligne de Cape Bathurst ») qui s'étend depuis l'ouest du Grand lac de l'Ours jusqu'au cap Bathurst. Cette structure pourrait définir la limite ouest de la Province des Esclaves et tronquer la zone magmatique du Grand lac de l'Ours (partie est de l'orogène de Wopmay). Les données laissent également supposer que la crête magnétique de Fort Simpson se poursuit à l'ouest de la faille de Tintina. Bien que l'anomalie semble avoir une source dans le socle cristallin, nous ne pouvons pas démontrer qu'elle représente une seule entité tectonique (terrain de Fort Simpson) sur toute sa longueur. Le style de chevauchement dans les collines Colville durant l'orogénèse de Forward (environ 1,66 Ga) prête à interprétation; la modélisation magnétique s'accommode de chevauchements qui mettent en jeu le socle cristallin, mais n'exclut pas les interprétations préconisant un charriage limité à la séquence de couverture.

INTRODUCTION

Aeromagnetic data have long been used as a basic tool for interpreting buried Precambrian basement terranes and, owing to improved acquisition and enhancement techniques, are now being used to examine poorly exposed sedimentary successions (e.g. Gunn, 1997; Peirce et al., 1998). Together with geochronological and Sm-Nd isotopic results obtained from drillhole samples, analysis of aeromagnetic data has been central to studies investigating crystalline basement hidden beneath Phanerozoic cover in western Canada (e.g. Hoffman, 1987; Ross et al., 1991; Villeneuve et al., 1993; Pilkington et al., 2000). These studies have significantly advanced models that address the tectonic evolution of the western Canadian Shield, link rocks of the Canadian Shield to Precambrian inliers in the Cordillera, and explore genetic relationships between the Precambrian and Phanerozoic geology of western Canada. Extension of such studies north of 60°N, however, has been hampered by gaps in the national aeromagnetic database.

Between 1998 and 2001, the Geological Survey of Canada collaborated with industry to acquire new high-resolution data over the northern Mackenzie Valley and adjacent areas (Fig. 1). These data represent part of an ongoing program to continue national aeromagnetic coverage into a region of long-standing hydrocarbon and mineral potential. The geometry and structure of Precambrian crystalline basement in the region are generally accepted as major influences on the Phanerozoic sedimentological, stratigraphic, and structural patterns that control potential economic deposits (e.g. Cecile et al., 1997). This paper focuses on analysis of this basement, using the new aeromagnetic data (and enhancements of older data) to consider the subsurface extent of the western Slave Province and the geometry of elements in northwestern Wopmay Orogen. In addition, data from Colville Hills are modelled to evaluate the question of crystalline basement faulting during the ca. 1.66 Ga Forward Orogeny.

Establishing the subsurface geometry of the Slave Province and Wopmay Orogen buried beneath Phanerozoic deposits and the Proterozoic successions A, B, and C (Fig. 1; Young et al., 1979) is of clear significance for diamond exploration. It is also important for reconstructions of the Neoproterozoic supercontinent Rodinia that linked northwestern Laurentia with Siberia and Australia in various configurations (e.g. Hoffman, 1991; Condie and Rosen, 1994; Rainbird et al., 1998; Thorkelson et al., 2001). As described below, the new data point to a hitherto unidentified structure, extending from Smith Arm of Great Bear Lake northwest to Cape Bathurst, that may define the western limit of the Slave Province and cut off the Great Bear magmatic zone in eastern Wopmay Orogen. In addition, the new data suggest that the Fort Simpson terrane in western Wopmay Orogen may continue in a curved trajectory as far west as the Tintina Fault, rather than following northward from Great Bear Lake to the Mackenzie Delta. Magnetic modelling along a seismic profile in the Colville Hills area yields results that are consistent with thick-skinned (involving crystalline basement) thrusting during the Forward Orogeny, as proposed by Cook and

MacLean (1992, 1995). This modelling, however, does not rule out the thin-skinned interpretations presented by Cook (1988).

DATA ACQUISITION

The data were acquired in four surveys, carried out by Sial Geosciences (in 1998), Questor Surveys (in 1999), Goldak Exploration Ltd. (in 2000), and Fugro Sial Airborne Surveys (in 2001). In the summer of 2002, an additional survey was flown over the Bonnet Plume Basin area (Fig. 1), the results of which remain confidential. Data were collected along approximately 259 605 line-km, with 800 m line spacing and 2.4 to 5 km tie-line spacing. The surveys were drape flown (constant height above terrain) with a mean clearance of 200 m.

WESTERN EXTENT OF SLAVE PROVINCE AND GREAT BEAR MAGMATIC ZONE

Wopmay Orogen records Paleoproterozoic accretionary tectonics on the western flank of the Slave Province. Key elements comprising Wopmay Orogen include (from east to west): the Asiatic fold-and-thrust belt; the Coronation margin (including the Coronation Supergroup, the metamorphic internal zone and the Hepburn intrusive suite); the Great Bear magmatic zone; the Hottah terrane; and the Fort Simpson terrane (Fig. 1; Bowring and Grotzinger, 1992 and references therein). Hottah terrane is considered to have formed, between ca. 1.94 and 1.90 Ga, outboard of the western margin of the Slave Province due to westward subduction of oceanic crust beneath an enigmatic ca. 2.4 to 2.0 Ga basement, and to have attached to the Slave Province at ca. 1.88 Ga (e.g. Bowring and Grotzinger, 1992). Subsequent eastward subduction of oceanic crust beneath the western flank of Hottah terrane, recently imaged by LITHOPROBE seismic-reflection profiling of the Slave-Northern Cordillera Lithospheric Evolution (SNORCLE; Cook et al., 1999), is interpreted to have generated ca. 1.88 to 1.84 Ga rocks in the Great Bear magmatic zone, as well as rocks of similar ages in Hottah terrane (Bowring and Grotzinger, 1992; Ross et al., 2000). Previous workers considered that calc-alkaline plutonic rocks in the Fort Simpson terrane (ca. 1.85–1.84 Ga; Villeneuve et al., 1991; Ross et al., 2000) formed due to west-dipping subduction of oceanic crust beneath the eastern edge of a microcontinent referred to as the 'Nahanni terrane' (Hoffman, 1989), and that the Fort Simpson arc and 'Nahanni terrane' docked with Hottah terrane after ca. 1.84 Ga (Hoffman, 1989). The Fort Simpson terrane, however, has been reinterpreted as a plutonic complex related to the recently imaged east-dipping subduction zone beneath western Hottah terrane (Cook et al., 1999). Furthermore, on the basis of SNORCLE, gravity, and drillhole data, the 'Nahanni terrane' ('Nahanni low', Fig. 2) has been reinterpreted as a sedimentary basin formed on attenuated crust of the Fort Simpson terrane rather than a microcontinent (Cook et al., 1999).

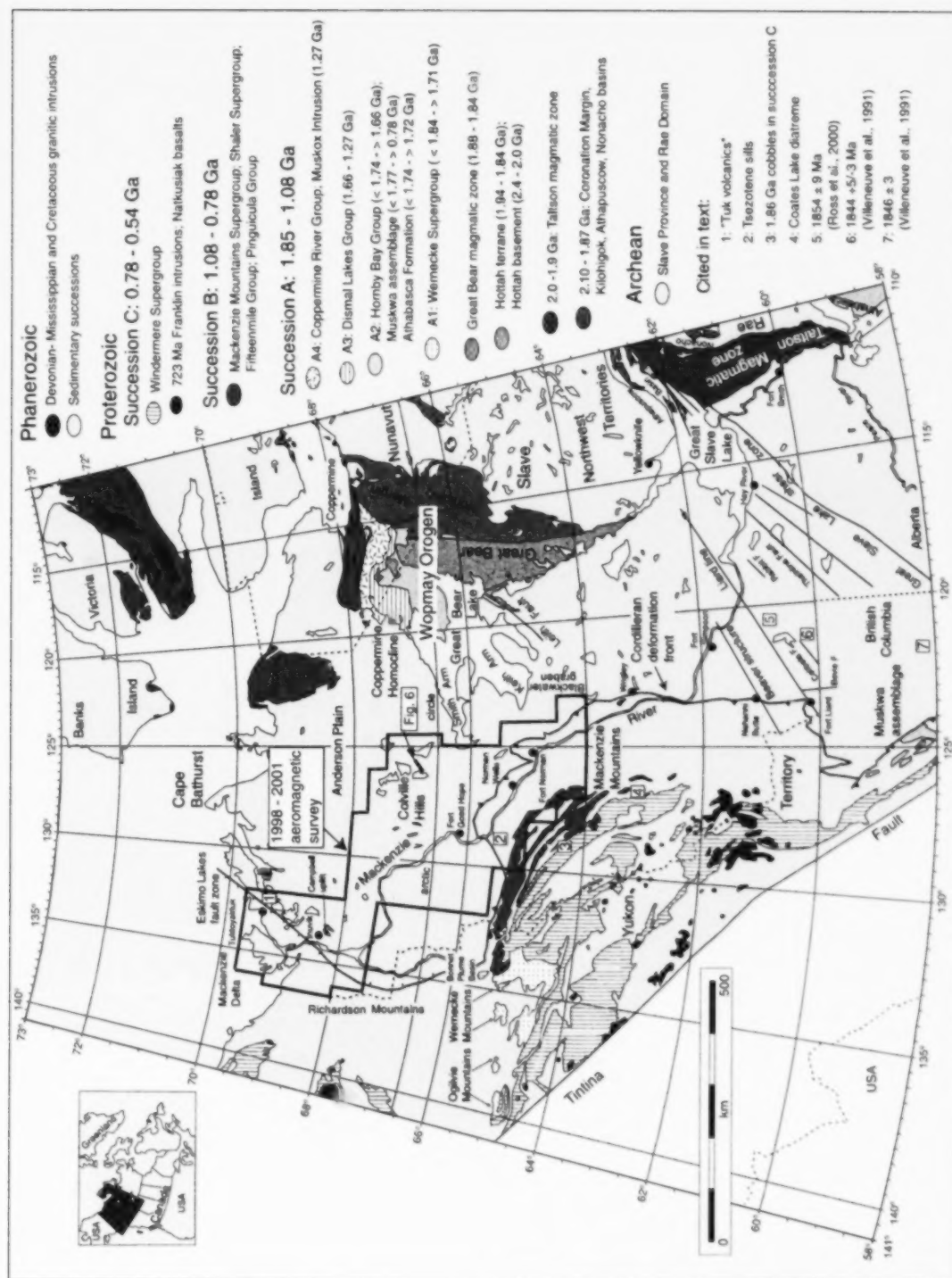


Figure 1. Major tectonic elements, northwestern Canada (after Wheeler *et al.*, 1996; successions A, B, and C after Young *et al.*, 1979; succession A1 to A4 designations after Cook and MacLean, 1995 and MacLean, 2002). Recent geochronology indicates that the Wernecke Supergroup was deposited before ca. 1710 Ma (age of Bonnet Plume intrusions; Thorkelson *et al.*, 2001) and that the Muskwa assemblage was deposited after 1766 ± 14 Ma (age of youngest detrital zircon, Ross *et al.*, 2001).

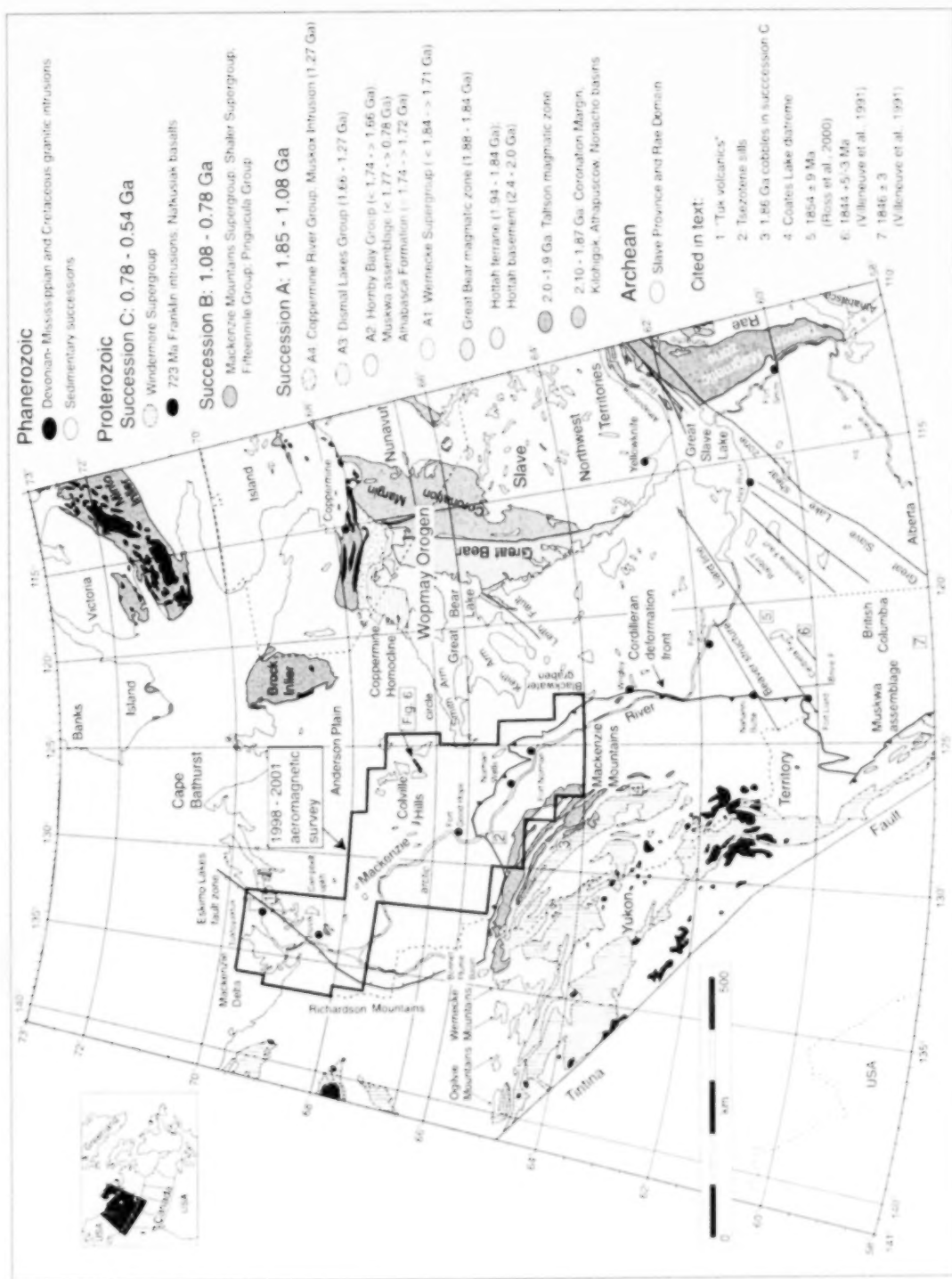


Figure 1. Major tectonic elements northwestern Canada after Wheeler et al., 1996, successions A, B and C after Young et al., 1979, succession A1 to A4 designations after Cook and MacLean, 1995 and MacLean, 2002. Recent geochronology indicates that the Wernecke Supergroup was deposited before ca. 1.70 Ma age of Bonnet Plume intrusions, Thorkelson et al., 2001 and that the Muskwa assemblage was deposited after 1.66 ± 0.14 Ma age of youngest detrital zircon, Ross et al., 2001.

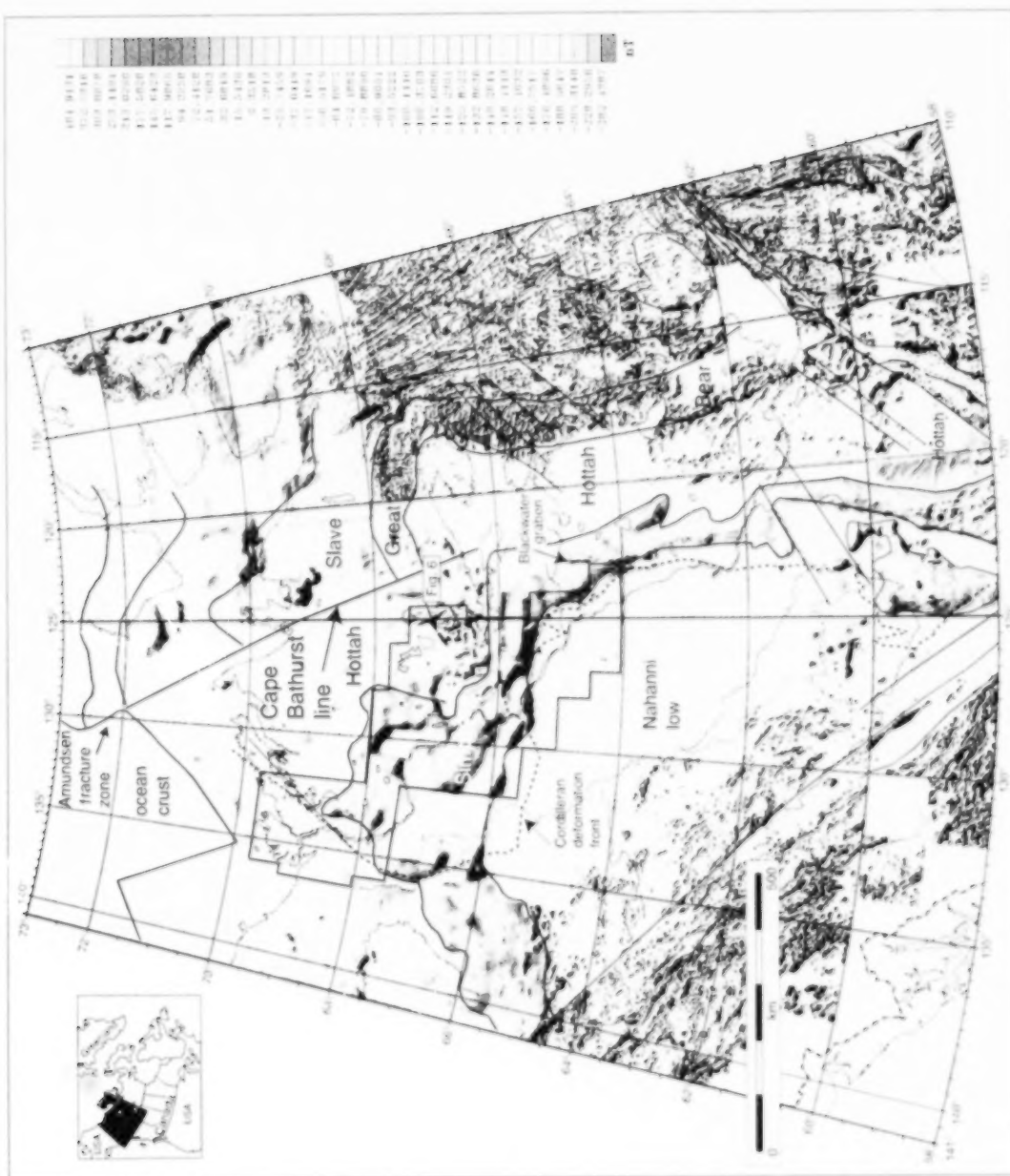


Figure 2. Total magnetic field, northwestern Canada

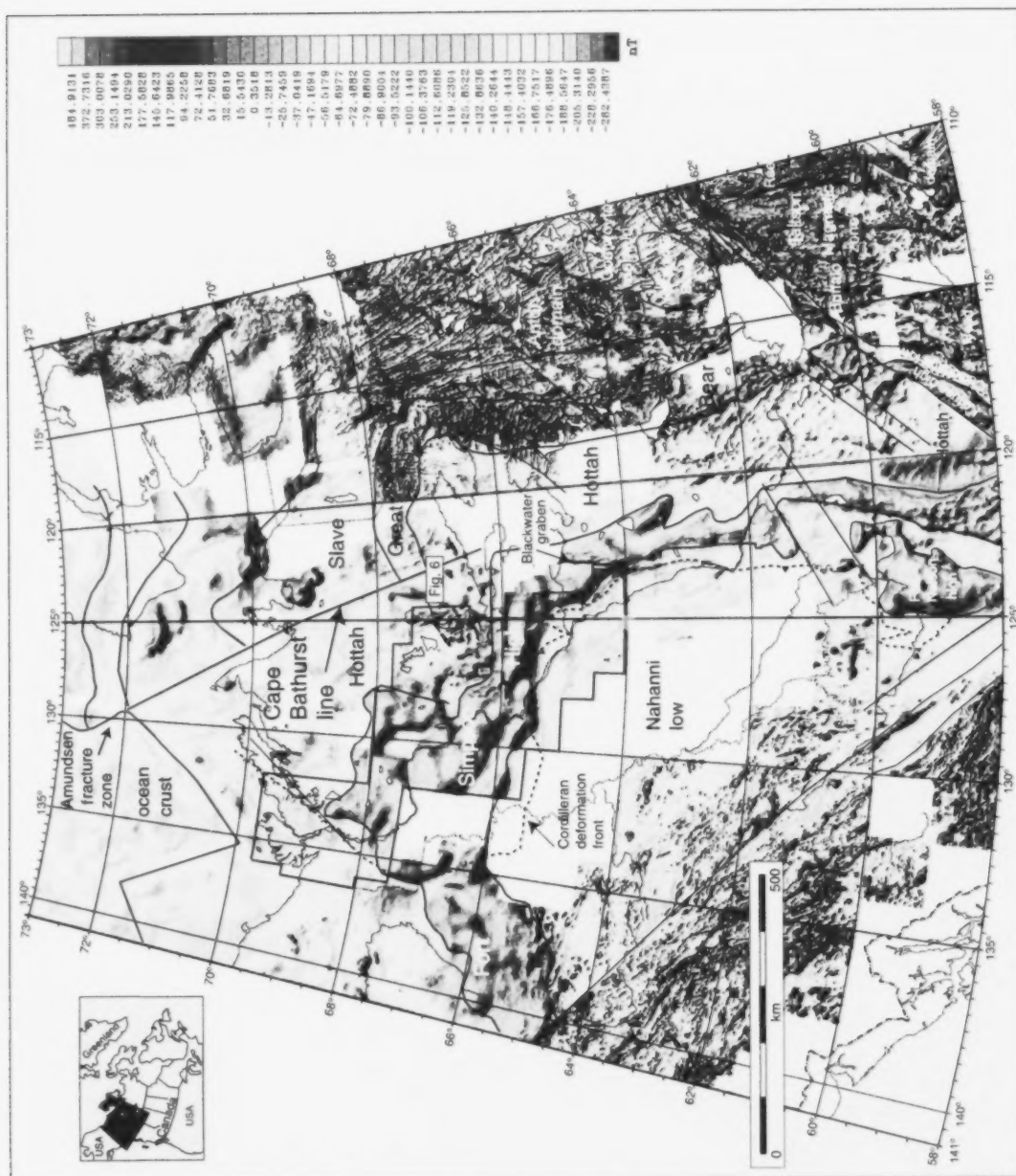


Figure 2. Total magnetic field, northwestern Canada.

The regional magnetic field data are illustrated in Figure 2. In order to suppress the effects of shallow magnetic sources and to emphasize regional geological structure, the data were filtered to remove all wavelength components less than 50 km (Fig. 3; lowpass filter). Between Great Slave and Great Bear lakes, the exposed part of the Great Bear magmatic zone is expressed aeromagnetically as a north-trending high with variably oriented internal swells and depressions (Fig. 2; e.g. Pilkington et al., 2000). North of Great Bear Lake, the zone disappears beneath Proterozoic strata of the Coppermine Homocline and, although attenuated by the cover rocks, its magnetic signal persists, undergoing a 90° bend to the west (e.g. Hoffman, 1987; Hildebrand and Baragar, 1991; Fig. 2). This east-west arm of the magmatic zone can be followed only for approximately 200 km farther west. The aeromagnetic high appears to terminate, as indicated by both the total magnetic field (Fig. 2) and the lowpass filtered field (Fig. 3). Similarly, the aeromagnetic low that defines Hottah terrane immediately south of the Great Bear magmatic zone appears to end, as do long-wavelength aeromagnetic high and low zones within the Slave Province (Fig. 2, 3). Collectively, these terminations outline a northwest-trending structure parallel to, and east of, Cape Bathurst. We interpret that this structure, herein referred to as the 'Cape Bathurst line', is a post-Wopmay Orogen fault that defines the western limit of the Slave Province.

Truncation of the Great Bear magmatic zone suggests that the Cape Bathurst line is younger than ca. 1.84 Ga. North of Great Bear Lake, high-frequency anomalies related to the Tweed Lake basalt (the subsurface equivalents of the Coppermine basalt; Sevigny et al., 1991; MacLean and Miles, 2002) continue across the line, suggesting that it is older than ca. 1.27 Ga, the age of the Mackenzie igneous event (LeCheminant and Heaman, 1989). The northern tip of the Cape Bathurst line coincides with the Amundsen fracture zone, a Cretaceous structure considered to have formed during northwestward opening of the Arctic Ocean (Lane, 1997). Apparently, the Cape Bathurst line acted as a crustal-scale discontinuity that helped dictate the geometry of Cretaceous rifting and the shape of the Canadian polar margin (see Lane, 1997). The southern extent of the Cape Bathurst line is unknown. Although the Cape Bathurst line is not well expressed in the Bouguer gravity field north of Great Bear Lake, it may account for the termination of the Bulmer Lake gravity high (Hornal et al., 1970; Johnny Hoe high of Hoffman, 1989) within Hottah terrane south of Great Bear Lake.

FORT SIMPSON TERRANE AND NAHANNI LOW

The Fort Simpson terrane is defined largely on the basis of the Fort Simpson magnetic high, a high-amplitude (averaging approx. 300 nT), approximately 100 km wide anomaly that is bounded by steep gradients and displays a bulbous to ovoid internal structure (Fig. 2; Hoffman, 1989; Villeneuve et al., 1991). Knowledge of the Fort Simpson terrane is based entirely on geophysical and drill-core data; interpretation of

the terrane as a calc-alkaline plutonic complex (see above) rests on its aeromagnetic character and on biotite granite samples recovered from one well in northern British Columbia and two wells in southern Northwest Territories, which have yielded U-Pb zircon ages of ca. 1.84 to 1.85 Ga (Villeneuve et al., 1991; Ross et al., 2000). The regional trace of the Fort Simpson magnetic high follows the general outline of Cordilleran structures (Villeneuve et al., 1991). It is north-trending from its southern limit in British Columbia until approximately 62°N, where it arcs gently west (Fig. 2). Near 65°N, it curves sharply west, concordant with the bend in the Great Bear magmatic zone described above, and continues to the Tintina Fault (Fig. 2). Local zones of diminished amplitude appear along the length of the Fort Simpson magnetic high, such as near two northeast-trending cross structures, the Liard line (e.g. Cecile et al., 1997) and the Beaver structure (Morrow and Miles, 2000). Similarly, local zones of enhanced amplitude occur, such as above the Blackwater graben (Fig. 1, 2), where short-wavelength magnetic highs (approx. 25 km) reflect filling by the Tweed Lake basalt (MacLean and Miles, 2002; cf. Cook et al., 1992). On the 50 km lowpass filter image (Fig. 3), the integrity of the anomaly as a long-wavelength feature is maintained continuously until the Tintina Fault.

Euler deconvolution modelling was used to gain a general indication of depth to the source of the long-wavelength anomaly that defines the Fort Simpson high (Fig. 4; see Reid et al., 1990). The Euler technique responds primarily to gradients in the data and therefore yields estimates of depths to the upper surfaces of magnetic bodies. The vertical spread of Euler depths at a given body edge arises from solutions being calculated from sample window locations not directly above the edge. In these cases, the shallower depth solutions are generally more reliable. The method requires specification of two variables: sample window size and structural index (a measure of the geometry of a magnetic source). In the present example, we selected a sample window of 20 km, which is small relative to the size of regional anomalies but permits relatively deep solutions, and a structural index of zero, which is suitable for two-dimensional features such as contacts across differently magnetized rock bodies. Depending on the geometry of specific sources, higher structural indices may be more appropriate. However, a constant value of zero permits consistent evaluation of magnetic contacts within regional sources that have diverse shapes. In addition, a structural index of zero produces conservative (minimum) depth solutions.

The Euler method yields estimated source depths of up to 10 km across the Fort Simpson anomaly west of Great Bear Lake (Fig. 4), values that are consistent with depths to crystalline basement based on seismic data in the Anderson Plain and Colville Hills areas to the north and east (MacLean and Cook, 1992; Cook and MacLean, 1995, 1996; MacLean and Cook, 1997; MacLean, 1999). Many of the depth solutions, however, point to shallow (<5 km) sources (Fig. 4). Some of these are known geological entities (e.g. Tweed Lake basalt), but most are not, implying that as yet unproven sills, flows, or dykes lie within the Proterozoic cover overlying crystalline basement. Although shallow bodies may, in some cases, yield



Figure 3. Magnetic field after application of 50 km low-pass filter (i.e. magnetic signals from sources with wavelengths less than 50 km removed)

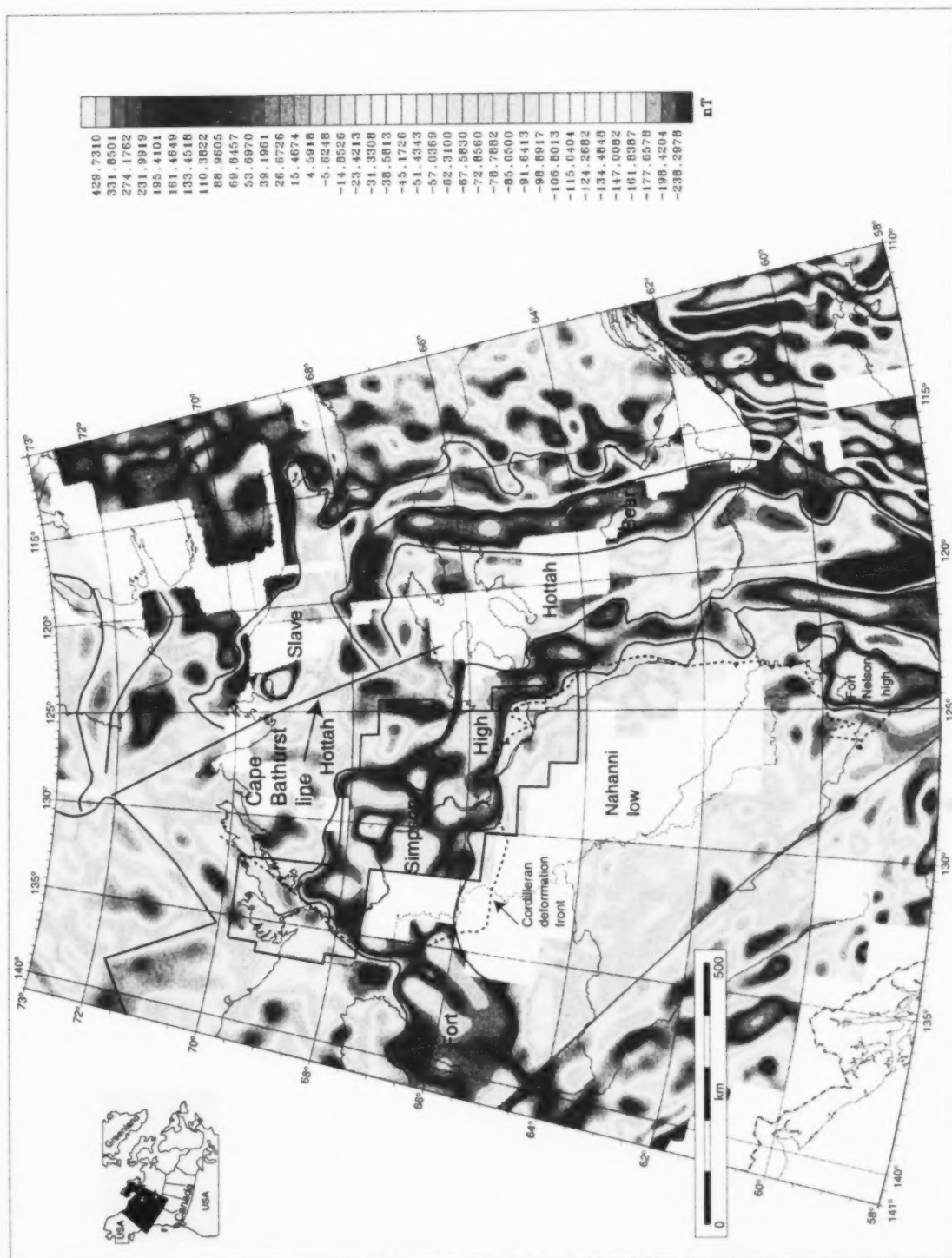


Figure 3. Magnetic field after application of 50 km lowpass filter (i.e. magnetic signals from sources with wavelengths less than 50 km removed).

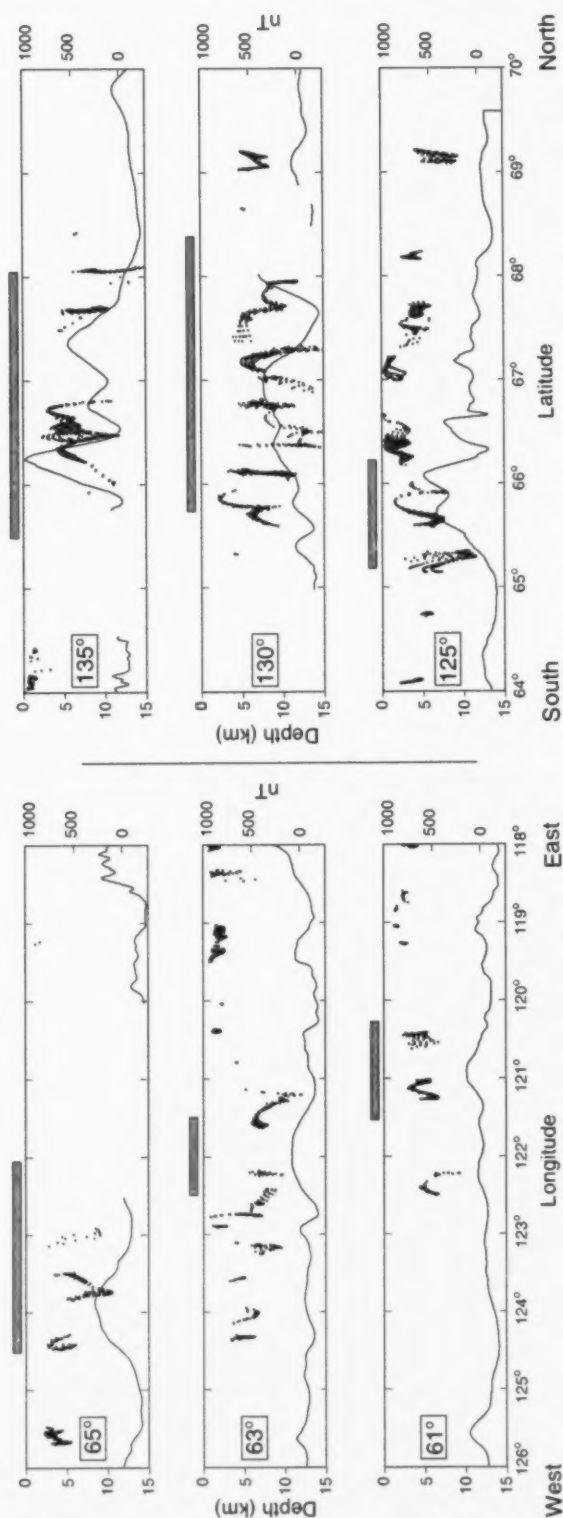


Figure 4. Profiles of depth solutions from Euler deconvolution (dots) and magnetic field (solid lines, in nT). Grey bars mark position of Fort Simpson magnetic high.

long-wavelength magnetic anomalies, we doubt that this is the case for the terrane underlain by the Fort Simpson high. First, between Fort Good Hope and Smith Arm of Great Bear Lake, the Tweed Lake basalt generates short-wavelength anomalies (20–25 km) that are superimposed on the long-wavelength Fort Simpson high (Fig. 3). Second, other known Proterozoic flows and sills are not marked by magnetic highs. These include sills that are likely part of the ca. 1.27 Ga Mackenzie igneous event identified in Succession A strata on seismic profiles north of the Colville Hills (e.g. Cook and MacLean, 1995); the Tsezotene mafic sills (ca. 780 Ma; LeCheminant and Heaman, 1994) in Succession B strata (Mackenzie Mountain Supergroup) west of Norman Wells (e.g. Cook and MacLean, 1999); and mafic volcanic rocks of uncertain age (ca. [?]780 Ma) found in wells near Tuktoyaktuk Peninsula ('Tuk volcanics'; Williams, 1986; Wielens, 1992). Third, for the Fort Simpson anomaly to be generated within Proterozoic cover, a correspondingly voluminous and extensive magmatic event capable of masking the effects of crystalline basement would be required. In short, although shallow sills or flows in the Proterozoic successions may well be portrayed by the Euler solutions, we infer that the Fort Simpson high evident on the total field (Fig. 2) and 50 km lowpass (Fig. 3) images represents a source within crystalline basement.

Even though the Fort Simpson anomaly likely reflects crystalline basement, we cannot demonstrate that it represents a single tectonic entity along its entire length. If the Fort Simpson terrane does continue west to the Tintina Fault, one implication is that ca. 2.4 to 2.0 Ga Hottah basement and 1.88 to 1.84 Ga Wopmay Orogen magmatic rocks underlie the Anderson Plain, the Mackenzie Delta, and the northern Yukon (Fig. 5). Considering that Devonian plutons in the northern Yukon contain a significant component of inherited zircon (Lane et al., 1993), a test of this hypothesis would be the discovery of basement xenoliths with Hottah basement and 1.88 to 1.84 Ga ages. We note that this geometry represents a return to an idea originally proposed by Coles et al. (1976), and is consistent with interpretations of minimal Cretaceous-Tertiary strike slip in Arctic Alaska and the northern Yukon (e.g. Lane, 1992).

Cook and Van der Velden (1993) postulated that the Wernecke Supergroup (at the base of Succession A in the Cordillera) was deposited above a west-facing crustal ramp that extended along the length of ancestral North America for at least 1500 km, from the Mackenzie Delta to the State of Washington. However, with the exception of a decrease in the magnetic field along a steep, north-west-facing gradient subparallel to Tuktoyaktuk Peninsula (Fig. 2), where seismic data indicate thinned Proterozoic crust (Stephenson et al., 1994;

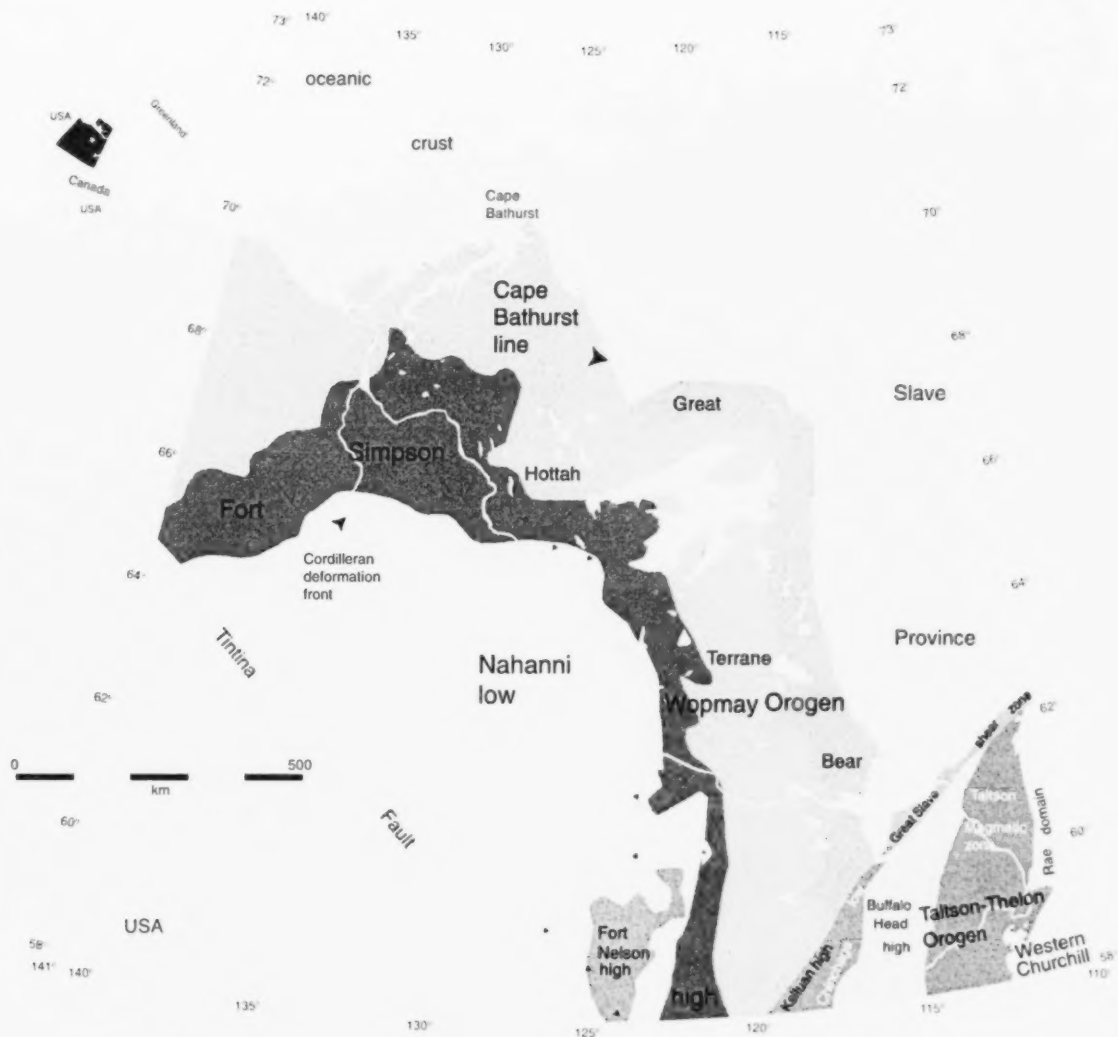


Figure 5. Interpreted basement tectonic domains and structural elements (modified after Hoffman, 1989; Ross et al., 1991; Pilkington et al., 2000). Continent-ocean boundary in Beaufort-Mackenzie area after Stephenson et al. (1994) and Lane (1997).

Lane, 1997), this postulated ramp does not have an aeromagnetic expression. In addition, although thick (approx. 13 km) Wernecke Supergroup strata appear to record stretching of ca. 1.84 Ga Wopmay Orogen crust before ca. 1710 Ma (the age of the Bonnet Plume intrusions; Thorkelson et al., 2001), it remains unclear if they were deposited in a single, continuous, west-facing, passive margin prism or in an intracratonic basin (Thorkelson et al., 2001). The nature of the Nahanni low basement, upon which Succession A strata were

deposited, is also uncertain. The Nahanni low may represent thinned Fort Simpson crust (Cook et al., 1999), but it may also contain other components, as suggested by a crystallization age of 1100 to 1175 Ma from a granite clast in a diatreme (Coates Lake diatreme) cutting Succession B rocks (Mackenzie Mountain Supergroup; Jefferson and Parrish, 1989; Fig. 1), and by 1.86 Ga cobbles in Succession C strata (Rapitan Group; Ross and Villeneuve, 1997; Fig. 1).



Figure 5. Interpreted basement tectonic domains and structural elements (modified after Hoffman, 1989; Ross et al., 1991; Pilkington et al., 2000). Continent-ocean boundary in Beaufort-Mackenzie area after Stephenson et al. (1994) and Lane (1997).

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MAGNETIC MODELLING OF FORWARD OROGEN STRUCTURE, COLVILLE HILLS

Drawing direct comparisons between the geology exposed in the Coppermine Homocline and interpretations of seismic data from the Colville Hills, Cook and MacLean (1995, 1996) defined the Forward Orogeny for structures found in sub-Dismal Lakes Group strata (Fig. 1). They considered that the Narakay volcanic rocks near the top of the Hornby Bay Group were synorogenic and, dated at 1663 ± 8 Ma (Bowring and Ross, 1985), defined the time of the orogeny.

Using seismic data from the easternmost Colville Hills, F.A. Cook and co-workers (Cook, 1988; Cook and Clark, 1990; Sevigny et al., 1991) interpreted that Proterozoic deformation reflected a classical thin-skinned foreland thrust-and-fold belt style, with listric piggyback thrusts that repeat stratigraphy and detach close to the contact between Proterozoic sedimentary strata and crystalline basement. This structural style was extended across the plains, north to the Mackenzie Delta (Cook, 1988) and west to the Fort Norman (Dredge Mitchelmore and Cook, 1994) and Fort Good Hope (Clark and Cook, 1992) areas. In marked contrast, and using virtually the same data, Cook and MacLean (1995, 1996) and MacLean and Cook (1992) considered that Forward Orogen structures represent thick-skinned broken foreland deformation (e.g. Jordan, 1995), in which crystalline basement and Proterozoic sedimentary cover deformed together along high-angle faults of inconsistent trend and vergence. As emphasized by Cook and MacLean (1995), the thick-skinned interpretation has significant regional implications: the amount of horizontal shortening required by large-scale, bedding-parallel thrust faults is greatly reduced; and the need for mechanical linkage via detachments beneath the entire Mackenzie corridor is not required.

As illustrated in Figure 6, we modelled the magnetic field data along seismic line 116A/110A from the eastern Colville Hills, a line for which two fundamentally different interpretations have been published (cf. Cook and MacLean, 1995, Fig. 11; Sevigny et al., 1991, Fig. 9). Susceptibility measurements are not available for the interpreted units; therefore, to keep the number of modelled parameters to a minimum, only the basement and basalt units are assigned non-zero susceptibilities. In these cases, their geometries are based on the seismic interpretation of Cook and MacLean (1995). Susceptibilities were then adjusted to fit the data. The magnetic field is dominated by an 80 nT high, which can be explained by the Tweed Lake basalt. This anomaly is superimposed on a longer wavelength high, coincident with the basalt anomaly, with an approximately 20 nT amplitude, which corresponds generally to the interpreted basement offset. However, because the inferred basement effect of approximately 20 nT is small, it could also be modelled by

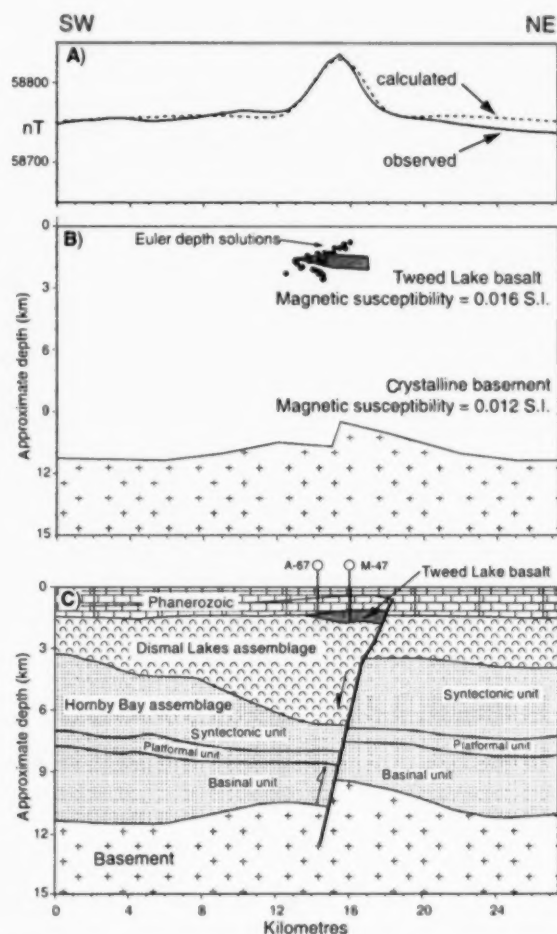


Figure 6. A) Magnetic field along seismic line 116A/110A. B) Magnetic model along seismic line 116A/110A. C) Geological interpretation of seismic line 116A/110A (from Cook and MacLean, 1995, Fig. 11; data acquired by Petro-Canada Inc.). As interpreted by Cook and MacLean (1995, 1996), during the Forward Orogeny, the fault in the centre of the profile was west-side-up (illustrated by arrow with white barbs); post-Dismal Lakes Group extensional reactivation (illustrated by arrow with black barbs) led to net west-side-down (i.e. normal) offset. Note that additional Cretaceous-Tertiary 'Laramide' reactivation resulted in reverse offsets of the sub-Phanerozoic unconformity and Phanerozoic markers. Tweed Lake A-67 and M-47 are two of four wells that penetrate the Tweed Lake basalt (see Sevigny et al., 1991; MacLean and Cook, 1992). See Figure 2 for location.

magnetization contrasts within the overlying Proterozoic section (cf. MacLean and Miles, 2002), without significant basement offset. In summary, although the aeromagnetic data can successfully model the thick-skinned interpretation on seismic line 116A/110A presented by Cook and MacLean (1995), a thin-skinned interpretation, such as that given by Sevigny et al. (1991), cannot be precluded.

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